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Relation of Ultrasonic Energy Loss Factors and Constituent Properties in Unidirectional Composites

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INTRODUCTION

Advanced fiber composites are inherently homogeneous materials whose properties may vary significantly due to small changes in fabrication procedure [1]. The nondestructive monitoring of composite material components for structural integrity assessment is important before and during structural service.

One of the major nondestructive evaluation techniques for monitoring composite materials is ultrasonic testing. It has been shown that ultrasonic wave parameters can be correlated with interlaminar strength [2], tensile strength [3-5] and transfiber compression fatigue [1]. Also, knowledge of the wave transmission characteristics of composites is important in the interpretation of acoustic emission [6] and in dynamic studies such as the assessment of impact damage vulnerability [7].

The narrow band ultrasonic longitudinal and shear wave group velocities and attenuations in the principal directions of a unidirectional Hercules AS/3501-6 graphite fiber epoxy composite and in the Hercules 3501-6 epoxy matrix were reported in [8]. A schematic of the composite laminate is shown in Fig. 1 and the examined wave modes are listed in Table 1. The purpose of this study is to develop an analysis which relates the composite energy loss behavior to the energy loss characteristics of the composite constituents.

PROPAGATION OF PLANE HARMONIC WAVES IN PRINCIPAL DIRECTIONS OF LINEAR VISCOELASTIC SOLID

If the amplitude of the stress wave is sufficiently small and the wavelength of the harmonic wave is much larger than the dimensions of the fiber and the fiber spacing, the composite may be modeled as a homogeneous anisotropic linear viscoelastic material. For plane longitudinal wave propagation along a principal direction x in an anisotropic linear viscoelastic rod, there is only one nonzero stress component which is defined as σ. The constitutive equation can be expressed in terms of the complex modulus as [9]

$$\sigma = E(1 + i\eta)\varepsilon \tag{1}$$

where E and ε are the elastic modulus and strain in the x direction, respectively, η is the loss factor for longitudinal wave propagation in the x direction, and i is the complex number defined by $\sqrt{-1}$. In general, both E and η are frequency-dependent but, in accordance with the assumption of linearity, are independent of the amplitude of stress and strain. The loss factor is often used to describe the energy dissipation property of a material and is defined as [10]

$$\eta = \frac{\Delta W}{2\pi W} \tag{2}$$

where ΔW is the energy dissipation per unit volume of material per cycle and W is the maximum (peak) potential energy within the cycle.

For a harmonic longitudinal wave of angular frequency ω(rad/sec) propagating in a linear viscoelastic rod, the phase velocity C_p and the attenuation α are [11]

$$C_p = \psi\sqrt{\frac{E}{\rho}} \quad \text{and} \quad \alpha = \beta\,\frac{\omega}{C_p} \tag{3}$$

where

$$\psi^2 = \frac{2(1+\eta^2)}{\sqrt{1+\eta^2}+1} \quad \text{and} \quad \beta = \frac{\sqrt{1+\eta^2}-1}{\sqrt{1+\eta^2}+1} \tag{4}$$

The loss factor η can be expressed explicitly in terms of the attenuation and the phase velocity as [12]

$$\eta = \tan\left(2\tan^{-1}\frac{\alpha C_p}{\omega}\right) . \tag{5}$$

Similar procedures can be applied to show that the shear wave phase velocity $(C_p)_s$ and attenuation α_s can be obtained from eqns. (3) and (4) by replacing E and η by G and η_s, respectively, where G is the shear modulus and η_s is the corresponding loss factor.

In addition to describing energy dissipation by the loss factor η or the attenuation α, there are several other parameters in common use. Relations can be obtained between these various parameters and are given in [6]. The loss tangent is simply

$$\tan\delta = \eta \tag{6}$$

and the logarithmic decrement is

$$\delta' = \frac{2\pi\alpha C_p}{\omega} \quad , \tag{7}$$

For small damping, eqns. (6) and (7) can be approximated as

$$\eta \approx \delta \approx \frac{\delta'}{\pi} \tag{8}$$

By assuming an idealized viscoelastic model such as the simple Voight model, the damping coefficient C can be expressed as

$$C = \frac{E\eta}{\omega} \quad . \tag{9}$$

The quality factor Q, the critical damping C_c and the damping ratio ζ are related by

$$\frac{1}{Q} = 2\zeta = \frac{2C}{C_c} = \eta \quad . \tag{10}$$

And, the relaxation time τ is defined by

$$\tau = \frac{C}{E} = \frac{\eta}{\omega} \quad . \tag{11}$$

Therefore, the loss factor η can be related by relatively simple expressions to the other commonly used dissipation parameters.

LOSS FACTOR OF GRAPHITE FIBER COMPOSITE BASED ON LOSS FACTORS OF ITS CONSTITUENTS

The narrow band group velocity and the attenuation for longitudinal wave propagation in Hercules 3501-6 epoxy matrix and along principal directions of unidirectional Hercules AS/3501-6 graphite fiber epoxy composites are reported in [8]. The experimentally measured fiber and void volume fractions of the composite were 53% and 6.4%, respectively. From those data the loss factor as described by eqn. (5) is evaluated for each mode of longitudinal wave propagation in the composite and the epoxy matrix and are shown in Figs. 2 and 3. If the constituent fibers and matrix are assumed to be linear isotropic viscoelastic materials, a loss factor of the composite for each mode of longitudinal wave propagation can be computed, based on the loss factors of the fibers and the matrix. Preliminary analysis (similar to that which follows) indicates that the resulting relationship between the loss factor of the composite and the loss factors of its constituent fibers and matrix is inconsistent with the experimental results. Thus, a new material called the "interface material" having unknown properties is introduced as an additional constituent of the composite.

It is postulated that the graphite fiber epoxy composite is a combination of fibers, matrix and interface material which, in part, can be thought of as regions weakened by voids entrapped during fabrication. Simplified models of this combination are shown

Figs. 4 and 5. Based on these models, expressions for the composite loss factors for different modes of longitudinal wave propagation along principal directions will be derived in terms of the loss factors of the constituents.

<u>Loss Factor of Unidirectional Composite for Longitudinal Wave Propagation in Fiber Direction</u>

The equivalent loss factor and elastic modulus of a unidirectional composite for longitudinal wave propagation in the fiber direction are derived next. The composite and its constituent fibers, matrix and interface material are assumed to be linear viscoelastic with constitutive relations in the fiber direction of the composite given by

$$E_f(1 + i\eta_f)\varepsilon_f = \sigma_f \tag{12}$$

$$E_m(1 + i\eta_m)\varepsilon_m = \sigma_m \tag{13}$$

$$E_{in}(1 + i\eta_{in})\varepsilon_{in} = \sigma_{in} \tag{14}$$

$$E_{co}(1 + i\eta_{co})\varepsilon_{co} = \sigma_{co} \tag{15}$$

where E is the elastic modulus, η is the loss factor, σ is the stress and the subscripts f, m and in refer to fiber, matrix and interface material, respectively, and the subscript co refers to the composite in the 0° fiber direction. With regard to Fig. 4, the average stress σ_{co} which acts on the cross-sectional area A of the unidirectional composite can be related to the stresses σ_f, σ_m and σ_{in}

which act on the cross-sectional areas of the fibers A_f, the matrix A_m and the interface material A_{in}, respectively. This can be written as

$$\sigma_{co} A = \sigma_f A_f + \sigma_m A_m + \sigma_{in} A_{in} \quad . \tag{16}$$

By assuming perfect bonding between the fibers, matrix and interface material, compatibility requires

$$\varepsilon_m = \varepsilon_f = \varepsilon_{in} = \varepsilon_{co} \quad . \tag{17}$$

The volume fractions of the fibers, matrix and interface material can be written, respectively, as

$$V_f = \frac{A_f}{A} \quad , \quad V_m = \frac{A_m}{A} \quad \text{and} \quad V_{in} = \frac{A_{in}}{A} \quad . \tag{18}$$

Substituting eqns. (12) to (15) into eqn. (16) gives

$$E_{co}(1 + i\eta_{co}) = E_f(1 + i\eta_f)\frac{A_f}{A} + E_m(1 + i\eta_m)\frac{A_m}{A} + E_{in}(1 + i\eta_{in})\frac{A_{in}}{A} \quad . \tag{19}$$

Substituting eqn. (18) into eqn. (19) gives

$$E_{co}(1 + i\eta_{co}) = E_f(1 + i\eta_f)V_f + E_m(1 + i\eta_m)V_m + E_{in}(1 + i\eta_{in})V_{in} \quad . \tag{20}$$

Separating the real and imaginary parts in eqn. (20) gives

$$E_{co} = E_f V_f + E_m V_m + E_{in} V_{in} \tag{21}$$

and

$$\eta_{co} = \frac{E_f V_f \eta_f + E_m V_m \eta_m + E_{in} V_{in} \eta_{in}}{E_{co}} \quad . \tag{22}$$

Substituting eqn. (21) into eqn. (22) gives .

$$\eta_{co} = \frac{\eta_f}{1 + \frac{E_m V_m}{E_f V_f} + \frac{E_{in} V_{in}}{E_f V_f}} + \frac{\frac{E_m V_m}{E_f V_f}\eta_m}{1 + \frac{E_m V_m}{E_f V_f} + \frac{E_{in} V_{in}}{E_f V_f}} + \frac{\frac{E_{in} V_{in}}{E_f V_f}\eta_{in}}{1 + \frac{E_m V_m}{E_f V_f} + \frac{E_{in} V_{in}}{E_f V_f}} \quad . \tag{23}$$

Assuming $\frac{E_m V_m}{E_f V_f} << 1$ and $\frac{E_{in} V_{in}}{E_f V_f} << 1$, eqn. (23) simplifies to

$$\eta_{co} = \eta_f + \frac{E_m V_m}{E_f V_f}\eta_m + \frac{E_{in} V_{in}}{E_f V_f}\eta_{in} \quad . \tag{24}$$

Eqns. (21) and either (23) or (24) describe the equivalent elastic modulus and the equivalent loss factor of the composite for longitudinal wave propagation in the fiber direction. If the volume fraction of interface material is zero, eqns. (21) and (24) simplify to

$$E_{co} = E_f V_f + E_m V_m \tag{25}$$

$$\eta_{co} = \eta_f + \frac{E_m V_m}{E_f V_f}\eta_m \quad . \tag{26}$$

Loss Factor of Unidirectional Composite for Longitudinal Wave Propagation Perpendicular to Fiber Direction

For longitudinal wave propagation perpendicular to the fiber direction, the equivalent elastic modulus and the equivalent loss factor can be obtained from the model shown in Fig. 5. A transverse stress σ_{c90} is applied to the composite. The resulting strains in the fiber, matrix, interface material and composite are, respectively,

$$\varepsilon_f = \frac{\sigma_{c90}}{E_f(1 + i\eta_f)} \tag{27}$$

$$\varepsilon_m = \frac{\sigma_{c90}}{E_m(1 + i\eta_m)} \tag{28}$$

$$\varepsilon_{in} = \frac{\sigma_{c90}}{E_{in}(1 + i\eta_{in})} \tag{29}$$

$$\varepsilon_{c90} = \frac{\sigma_{c90}}{E_{c90}(1 + i\eta_{c90})} \tag{30}$$

where the subscript c90 refers to the composite in a direction that is perpendicular to the fibers and where these constitutive equations contain the equilibrium conditions of equal stress on each constituent. Because the fibers, matrix and interfaces are in series with respect to the loading direction, the composite strain is related to the strains in the constituents by

$$\varepsilon_{c90} = V_f\varepsilon_f + V_m\varepsilon_m + V_{in}\varepsilon_{in} \quad . \tag{31}$$

Substitution of eqns. (27) to (30) into eqn. (31) and separation of the real and imaginary parts give

$$\frac{1}{E_{c90}(1 + \eta_{c90}^2)} = \frac{V_f}{E_f(1 + \eta_f^2)} + \frac{V_m}{E_m(1 + \eta_m^2)} + \frac{V_{in}}{E_{in}(1 + \eta_{in}^2)} \tag{32}$$

and

$$\frac{\eta_{c90}}{E_{c90}(1 + \eta_{c90}^2)} = \frac{V_f\eta_f}{E_f(1 + \eta_f^2)} + \frac{V_m\eta_m}{E_m(1 + \eta_m^2)} + \frac{V_{in}\eta_{in}}{E_{in}(1 + \eta_{in}^2)} \quad . \tag{33}$$

It is assumed that the damping is small and so the terms $(1 + \eta_j^2)$ can be approximated by unity; thus eqns. (32) and (33) become

$$\frac{1}{E_{c90}} = \frac{V_f}{E_f} + \frac{V_m}{E_m} + \frac{V_{in}}{E_{in}} \tag{34}$$

$$\frac{\eta_{c90}}{E_{c90}} = \frac{V_f\eta_f}{E_f} + \frac{V_m\eta_m}{E_m} + \frac{V_{in}\eta_{in}}{E_{in}} \quad . \tag{35}$$

Substitution of eqn. (34) into eqn. (35) gives

$$\eta_{c90} = \frac{\frac{E_{in}V_m}{E_mV_{in}}\eta_m}{1 + \frac{E_{in}V_m}{E_mV_{in}} + \frac{E_{in}V_f}{E_fV_{in}}} + \frac{\eta_{in}}{1 + \frac{E_{in}V_m}{E_mV_{in}} + \frac{E_{in}V_f}{E_fV_{in}}} + \frac{\frac{E_{in}V_f}{E_fV_{in}}\eta_f}{1 + \frac{E_{in}V_m}{E_mV_{in}} + \frac{E_{in}V_f}{E_fV_{in}}} \quad . \tag{36}$$

Eqns. (34) and (36) describe the equivalent elastic modulus and the equivalent loss factor of the composite for longitudinal wave propagation perpendicular to the fiber direction. If the volume fraction of interface material V_{in} is zero, eqns. (34) and (36) simplify to

$$\frac{1}{E_{c90}} = \frac{V_m}{E_m} + \frac{V_f}{E_v} \tag{37}$$

$$\eta_{c90} = \eta_m + \frac{E_mV_f}{E_fV_m}\eta_f \tag{38}$$

where the approximation preceding eqn. (24) have been used.

RESULTS AND DISCUSSION

The extensional moduli of the unidirectional AS/3501-6 graphite fiber epoxy composite as computed from the velocity and density measurements are 112 GN/m^2 (16.25 mpsi), 11.67 GN/m^2 (1.69 mpsi) and 8.58 GN/m^2 (1.24 mpsi) for the x_1, x_2 and x_3 directions, respectively. The modulus of the epoxy matrix as computed from the velocity and density measurements is 8.94 GN/m^2 (1.29 mpsi). The modulus of the fibers is 205 GN/m^2 (29.8 mpsi). The experimental frequency-dependent loss factors are given in Figs. 2 and 3. As mentioned earlier, the fiber, matrix and void volume fractions are 53%, 40.6% and 6.4%, respectively; and using eqns. (26) and (38) for a composite with no interface material, the composite loss factors could not be verified experimentally.

The new constituent defined as the interface material is considered to be a linear viscoelastic material having, as yet, unknown properties. Because the attenuation of the longitudinal wave in the x_3 direction is much higher than the attenuation in the x_2 direction, the interface material is assumed to have different properties in the x_2 and x_3 directions. More specifically, the interface material is assumed to be transversely isotropic with the same properties in the x_1 and x_2 directions. Therefore, there are seven unknown parameters: E_{in} and η_{in} which are transversely isotropic, and V_{in}, V_m and η_f. With the experimental data and the additional identity

$$V_f + V_m + V_{in} = 1 \quad , \tag{39}$$

eqns. (21), (23), (34) and (36) can be solved for the values of the seven unknowns. Note that in accordance with the transversely isotropic assumption for the interface material, eqns. (34) and (36) must be written twice, once each for the x_2 and x_3 directions.

Using the results in Figs. 2 and 3 and the seven equations cited above, with the nominal composite described by

$$\begin{aligned} E_f &= 205\ \frac{GN}{m^2}\ (29.8\ \text{mpsi}) \qquad & V_f &= 53\% \ , \ V_{voids} = 6.4\% \\ E_m &= 8.94\ \frac{GN}{m^2}\ (1.29\ \text{mpsi}) \qquad & V_m &= 40.6\% \ , \end{aligned} \tag{40}$$

the consistent linear viscoelastic model gives

$$\begin{aligned} E_f &= 205\ \frac{GN}{m^2}\ (29.8\ \text{mpsi}) \qquad & V_f &= 53\% \\ E_m &= 8.94\ \frac{GN}{m^2}\ (1.29\ \text{mpsi}) \qquad & V_m &= 32.4\% \end{aligned}$$

$$E_{in} = \begin{cases} 3.12\ \dfrac{GN}{m^2}\ (0.450\ \text{mpsi}),\ \text{in } x_1 \text{ and } x_2 \text{ directions.} \\ 1.88\ \dfrac{GN}{m^2}\ (0.274\ \text{mpsi}),\ \text{in } x_3 \text{ direction} \end{cases}$$

$$V_{in} = 14.6\% \ . \tag{41}$$

For consistency, E_f, V_f and E_m were maintained fixed when going from the nominal composite to the consistent linear viscoelastic composite. The corresponding loss factors of the interface material in the x_1, x_2 and x_3 directions are shown in Fig. 6.

The results given in eqn. (41) and Fig. 6 support the concept of the interface material as one of the composite constituents.

It is important to note that the interface material is an equivalent volume of material which, if included as a constituent of the composite, results in the measured velocities and attenuations. Thus, the losses which are attributed to the interface material may, in fact, be due to mechanisms such as scattering due to voids and delaminations. Although there has been no attempt to relate the loss factor of the composite to loss factors of the constituents in the shear modes, the analysis developed is still valid for shear wave propagation if the extensional variables are replaced by their corresponding shear variables.

For longitudinal wave propagation in the composite, the contribution from loss factors of the fiber, matrix and interface material are weighted as

$$\eta_c = A_{f,j}\eta_f + A_{m,j}\eta_m + A_{in,j}\eta_{in} \tag{42}$$

where the parameters $A_{f,j}$, $A_{m,j}$ and $A_{in,j}$ are the weighting constants for the fiber, matrix and interface material, respectively. The j subscript distinguishes between weighting parameters for the x_1, x_2 and x_3 directions. According to eqn. (23), the weighting parameters for the longitudinal wave in the fiber direction (x_1) are

$$A_{f,} = \frac{1}{1 + \frac{E_m V_m}{E_f V_f} + \frac{E_{in} V_{in}}{E_f V_f}} \tag{43}$$

$$A_{m,0} = \frac{\frac{E_m V_m}{E_f V_f}}{1 + \frac{E_m V_m}{E_f V_f} + \frac{E_{in} V_{in}}{E_f V_f}} \tag{44}$$

$$A_{in,0} = \frac{\frac{E_{in} V_{in}}{E_f V_f}}{1 + \frac{E_m V_m}{E_f V_f} + \frac{E_{in} V_{in}}{E_f V_f}} \; . \tag{45}$$

For longitudinal wave propagating perpendicular to the fiber direction (x_2 or x_3), the weighting parameters from eqn. (36) are

$$A_{f,90} = \frac{\frac{E_{in} V_f}{E_f V_{in}}}{1 + \frac{E_{in} V_f}{E_f V_{in}} + \frac{E_{in} V_m}{E_m V_{in}}} \tag{46}$$

$$A_{m,90} = \frac{\frac{E_{in} V_m}{E_f V_{in}}}{1 + \frac{E_{in} V_f}{E_f V_{in}} + \frac{E_{in} V_m}{E_m V_{in}}} \tag{47}$$

$$A_{in,90} = \frac{1}{1 + \frac{E_{in} V_f}{E_f V_{in}} + \frac{E_{in} V_m}{E_m V_{in}}} \; . \tag{48}$$

The numerical values for the longitudinal wave weighting parameters are summarized in Table 2.

The fiber loss factor η_f has been calculated and its behavior follows the curve in Fig. 2 within 5% to 10%. So, from Table 2, the results indicate that for longitudinal wave propagation in the fiber direction, the composite energy dissipation is due mainly to the fiber. Also, the composite energy dissipation along the other two directions is due mainly to the matrix and the interface material.

CONCLUSIONS

Ultrasonic attenuation and velocity measurements were previously conducted for longitudinal wave propagation in the Hercules 3501-6 epoxy matrix and in the principal directions of the unidirectional Hercules AS/3501-6 graphite fiber epoxy composite [8]. In the present study, the wave propagation results have been interpreted by considering the composite and the epoxy matrix as linear viscoelastic media. The loss factors were computed and plotted for longitudinal wave propagation in the principal directions of the composite and in the epoxy matrix.

It was observed that the experimental values of the loss factors of the composite could not be rationalized to simple parallel and series models if the composite was assumed to be comprised exclusively of fibers, matrix and voids. It was concluded that in addition to the fibers and the matrix, a new interface material was needed to obtain consistent results between the simple parallel and series models and the experiments. The composite, fibers, matrix and interface material were each assumed to be linear viscoelastic materials. The fibers and the matrix were assumed to be isotropic and the interface material was assumed to be transversely isotropic. The properties of the interface material were determined for longitudinal wave propagation along the principal directions of the composite. For longitudinal wave propagation in the composite, the contributions of the loss factors of the fibers, matrix and interface material to the composite loss factors were expressed in a single equation with weighting coefficients.

It is important to note that the numerical values of the loss factors apply only to the AS/3501-6 unidirectional composite with a 53% fiber volume fraction and a 6.4% void volume fraction. However, the concept of the equivalent dissipative interface material is useful for the quality control of otherwise like composites and for consistent wave propagation studies.

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TABLE 1: Propagation and Particle Motion Directions for Measurements of Group Velocity and Attenuation [8]

	Propagation Direction	Particle Motion Direction	Notation
Longitudinal Wave	x_1	x_1	$LW(x_1)$
	x_2	x_2	$LW(x_2)$
	x_3	x_3	$LW(x_3)$
Shear Wave	x_1	x_2	$SW(x_1);\ x_2$
	x_1	x_3	$SW(x_1);\ x_3$
	x_2	x_1	$SW(x_2);\ x_1$
	x_2	x_3	$SW(x_2);\ x_3$
	x_3	x_2	$SW(x_3);\ x_2$
	x_3	x_1	$SW(x_3);\ x_1$

TABLE 2: Weighting Factors for Contributions from Loss Factors of Composite Constituents Towards Loss Factor of Composite

Direction of Longitudinal Wave Propagation	Fiber	Matrix	Interface Material
x_1	0.9701	0.0258	0.0041
x_2	0.0302	0.4233	0.5465
x_3	0.0222	0.3111	0.6667

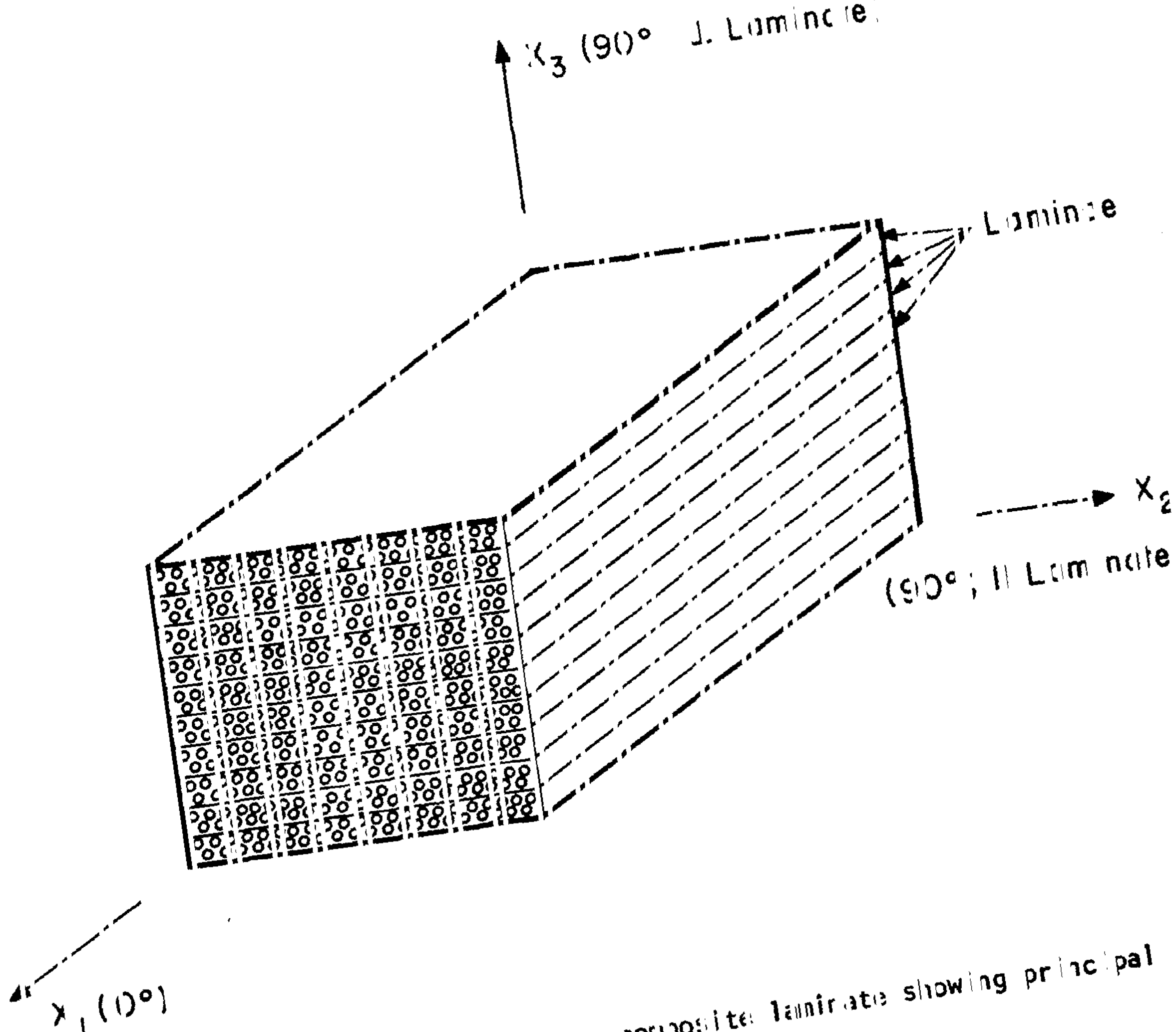

Fig. 1 Schematic of graphite epoxy composite laminate showing principal directions

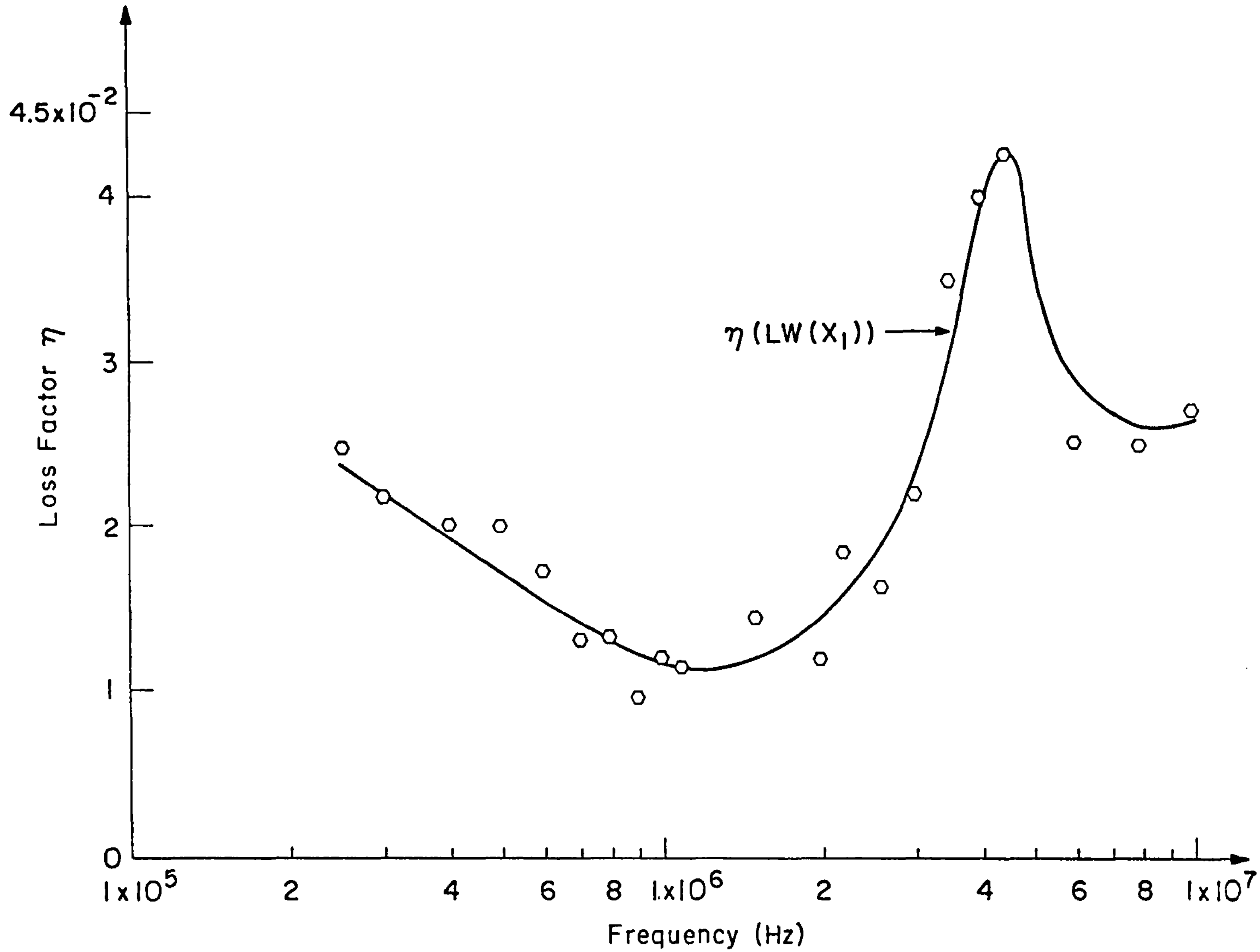

Fig. 2 Loss factor for longitudinal wave propagation in AS/3501-6 graphite fiber epoxy composite in the indicated direction.

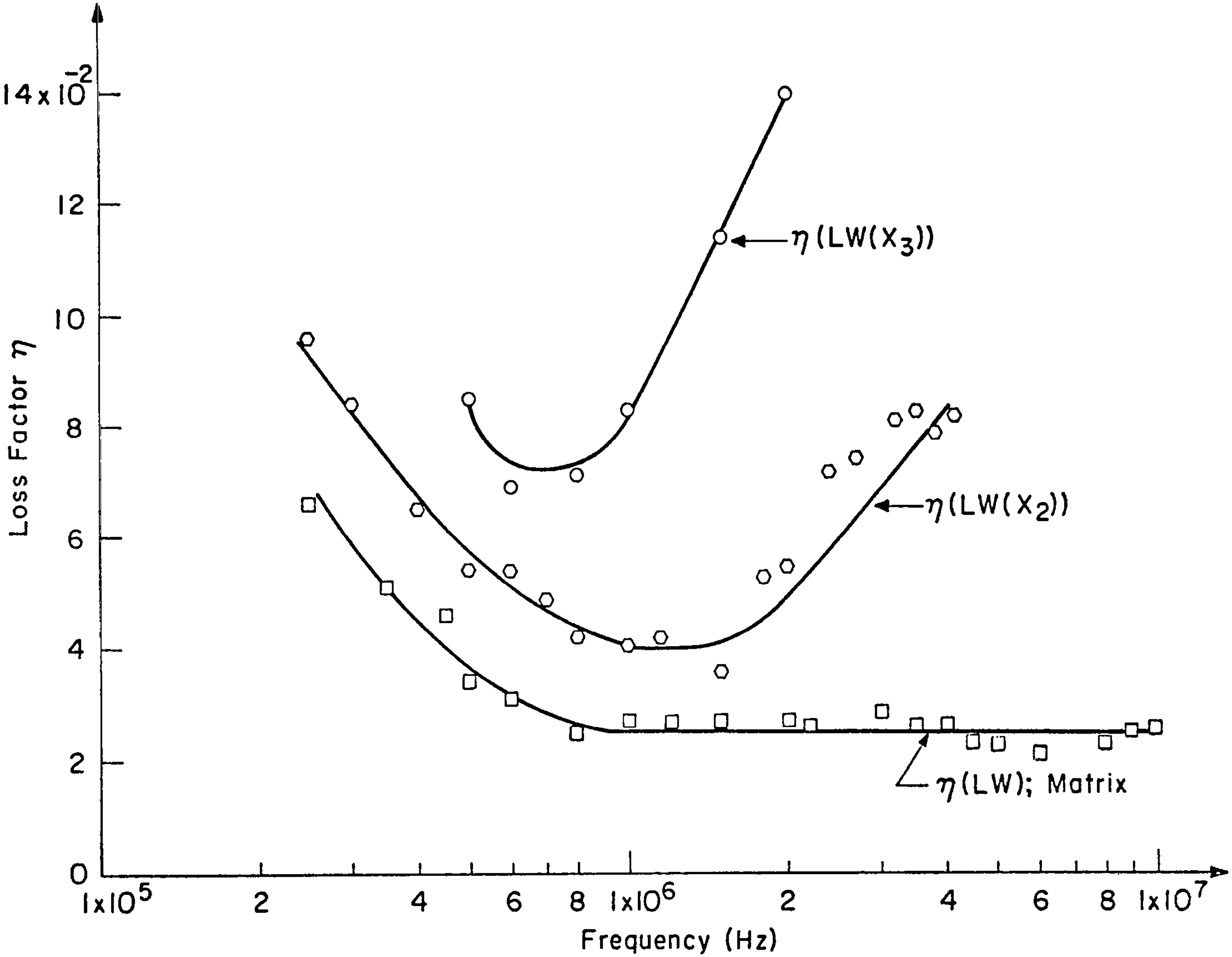

Fig. 3 Loss factor for longitudinal wave propagation in AS/3501-6 graphite fiber epoxy composite in the indicated directions and 3501-6 epoxy matrix.

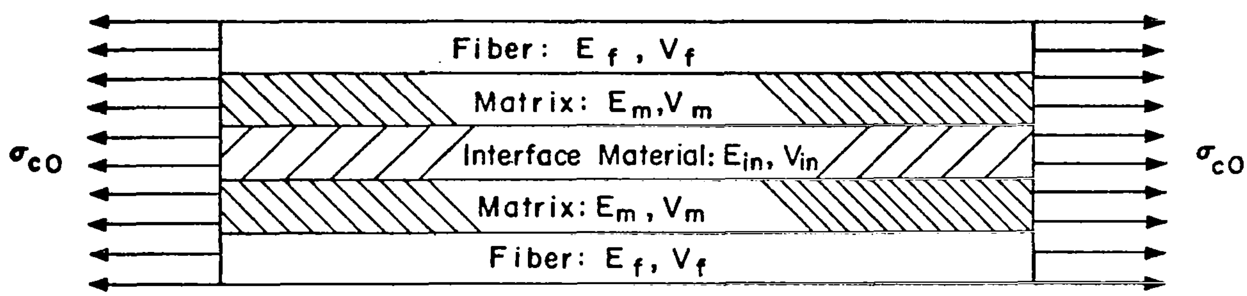

Fig. 4 Schematic of composite volume element containing fiber, matrix and interface material with loading in fiber direction.

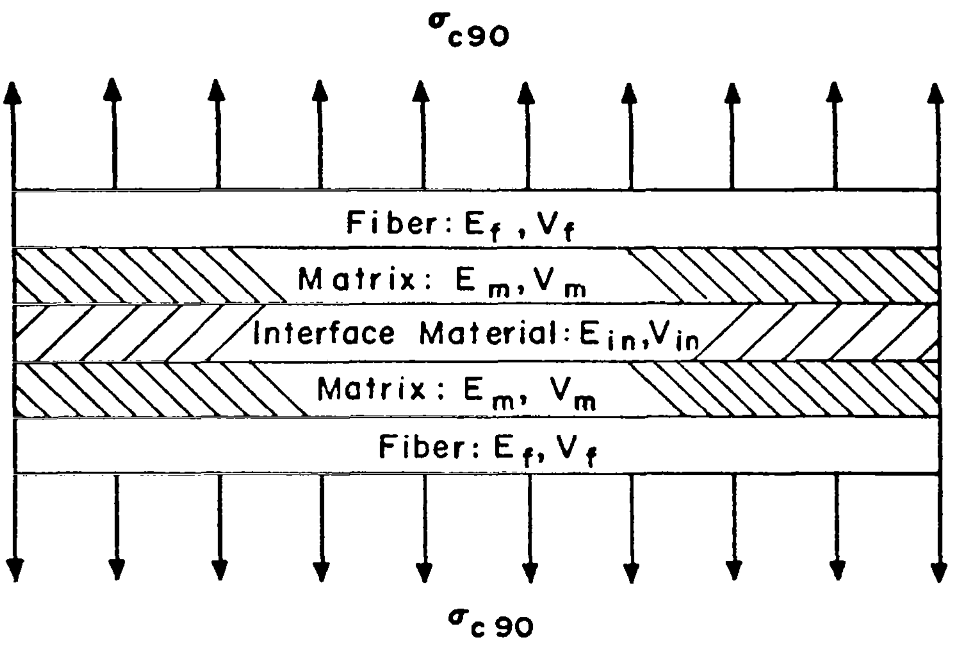

Fig. 5 Schematic of composite volume element containing fiber, matrix and interface material with loading perpendicular to fiber direction.

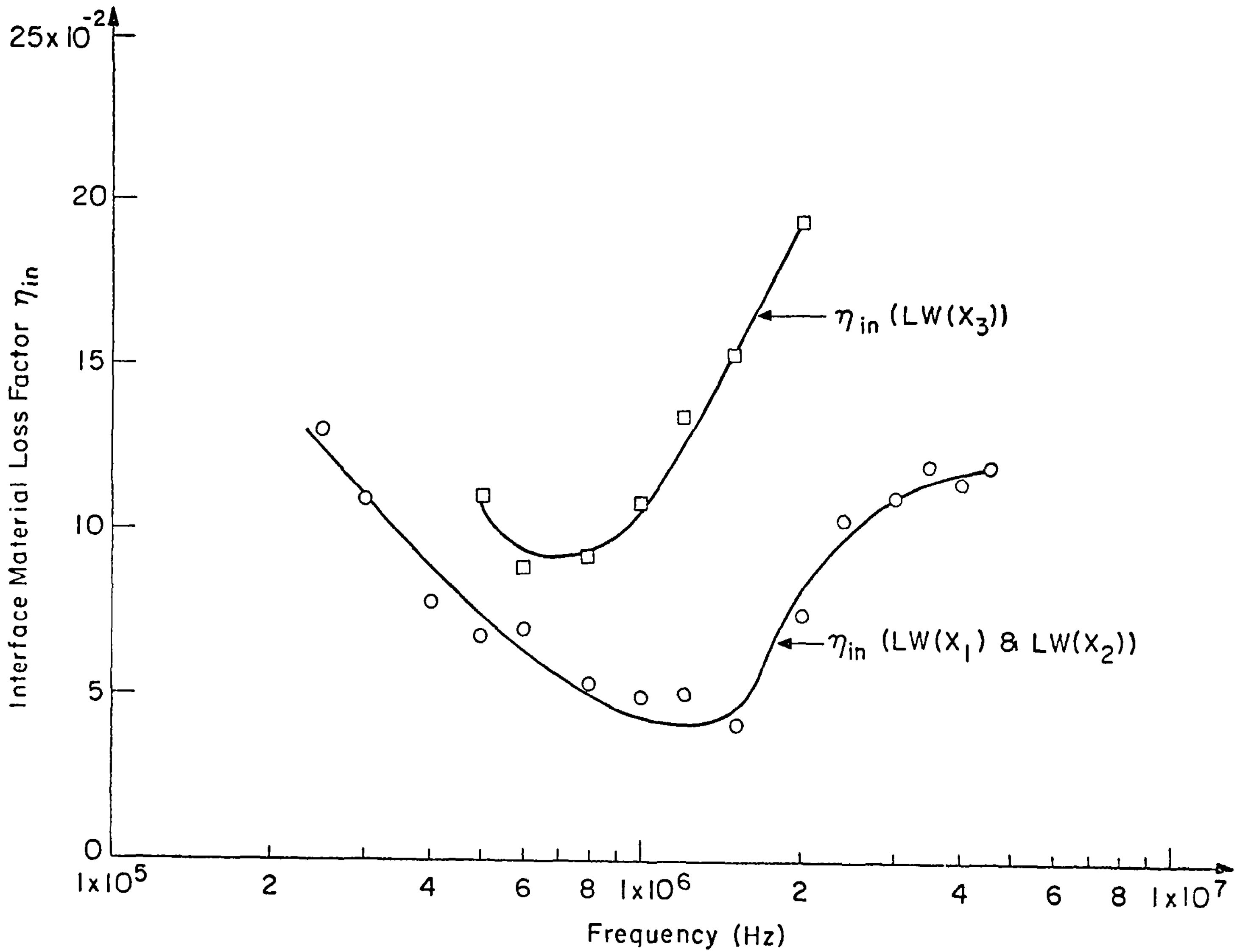

Fig. 6 Loss factor of AS/3501-6 Interface material for longitudinal wave propagation in the indicated directions.

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15. Supplementary Notes

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16. Abstract

A model is developed relating composite constituents properties with ultrasonic energy loss factors for longitudinal waves propagating in the principal directions of a unidirectional graphite/epoxy fiber composite. All the constituents are assumed to behave as linear viscoelastic materials with energy dissipation properties defined by loss factors. It is found that by introducing a new constituent called the interface material, the composite and constituent properties can be brought into consistency with simple series and parallel models. An expression relating the composite loss factors to the loss factors of the constituents is derived and its coefficients are evaluated.

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